Urban Forestry & Urban Greening 29 (2018) 212–222

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy

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ARTICLE INFO

Keywords:
ENVI-met
Green infrastructure
Microclimatic mitigation strategies
Urban heat island
Urbanization

ABSTRACT

Incorporation of strategic green infrastructure into urban settings has a potential to mitigate climate change, urban heat island (UHI) effect, flood risk and subsequent increase in quality of human life in general. UHI induces through low surface albedo, building geometry and absence of greenery and it deteriorates the thermal comfort and well-being of city dwellers and occupants. This study examined the implication of urban green infrastructure on enhanced microclimatic condition in tropical urban perspective while evaluating the best suitable strategy by modeling a designated site with ENVI-met microclimatic software (V4). The calibration procedure of ENVI met has been undertaken through a real ground monitoring process and the software modeling was done for selected urban setting. The model was firstly validated by reconciliation of observed in-situ measurements with simulated values. *R*-squared (R^2) values for three different surface types such as asphalt, cement and grass were 0.91, 0.96, 0.88 for near ground (0m) and 0.78, 0.81, 0.92 for 1.5 m, respectively. The parametric studies verified that ENVI-met model can be effectively utilized to improve urban micro-scale thermal conditions in tropical Sri Lanka. The numerical simulation model of ENVI-met was used to generate micro-climatic data for the selected area of Colombo metropolitan region with six greening design scenarios such as prevailing UHI condition (T1), trees in curbsides (T2), 100% green roofing (T3), 50% green roofing (T4), 50% green walls (T5) and a combination (T6) of above mentioned green strategies (trees in curbsides + 50% green roofs + 50% green walls). Temperature reductions obtained from all green strategies were compared with existing UHI (T1) scenario during peak temperature in given time. The temperature reductions accomplished by T2, T3, T4, T5 and T6 green infrastructure options compared to T1 were 1.87 °C, 1.76 °C, 1.79 °C, 1.86 °C and 1.90 °C, respectively. It can be concluded that strategic design of urban greenery can effectively enhance the urban environment and outdoor thermal comfort in tropical Sri Lanka.

1. Introduction

The present world population is 7.5 billion and it is currently (2017) growing at a rate of around 1.11%per year and it is estimated to reach 10 billion by 2056. In addition, 6 billion live in less developed countries and 1.2 billion live in more developed countries including 54.7% (2017) of the world's population living in urban areas (UN DESA, 2017; PRB, 2014). As predicted by UN, 60% of the future world population of 8.5 billion will be categorized as urban population by 2030 (UN, 2015) and the number of cities with population of over one million in 2016 was 512 and it is expected to increase by approximately 30% into 662 by 2030 (UN DESA, 2017; Mirzaei and Haghighat, 2010). Concentration of sophisticated resources, commercial assets, beneficial socio-economic and environmental conditions and modern infrastructure will encourage people to move into a single, favorable place which is called as urbanization. Urbanization can bring both positive and negative consequences to human, society, economy and natural and built environment. With the process of endless development and anthropogenic interventions occurred with urbanization and industrialization, can bring formidable challenges originated from both Urban Heat Island effect (UHI- defined as a city or metropolitan area that is significantly warmer than its surrounding rural areas due to anthropogenic activities) and climate change.

The Intergovernmental Panel on Climate Change (IPCC) has developed heat island intensities varying in the range of 1.1–6.5 °C (IPCC, 2014).The city of Medellin (Colombia) recorded positive daytime UHI of 7.0 °C, followed by Tokyo (Japan), Nagoya (Japan), Sao Paulo (Brazil), and Bogota (Columbia) (> 5 °C) (Peng et al., 2012). The

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https://doi.org/10.1016/j.ufug.2017.11.013
Received 29 March 2017; Received in revised form 17 November 2017; Accepted 17 November 2017
Available online 22 November 2017
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average temperature in the urban microclimate can be increased in the range of 1–12 °C warmer than the surrounding area in larger cities having over one million population. Further, Smaller cities where the population below 1 million is less vulnerable for heat islands compared to larger cities. Major reasons which instigate the UHI are low surface albedo, building geometry and orientation and lack of greenery within the micro-climate (Taha et al., 1988; Taha, 1997). However, basically UHI occurs when naturally available vegetated surfaces (such as grass and trees) are replaced with non-natural heat absorbing, non-reflective, water-resistant impervious surfaces (such as concrete, asphalt) made with anthropogenic materials which absorb high percentages of incoming solar radiation (Wijeratne and Hulwatura, 2016; Taha et al., 1988; Taha, 1997). Moreover, UHI intensities are affected by factors such as wind speeds, cloud cover, season, city and population size, and time of the day (Arnfield, 2003).

This UHI can directly influence on decreasing thermal comfort and healthiness of city dwellers and occupants. Impacts such as deterioration of the conditions in living environments, increment of energy consumption can be directly occurred due to UHI. Further, UHI can augment air conditioning demand (Rosenfeld et al., 1993), enhanced air pollution (Hogrefe et al., 2004) and heat-stress associated mortality and illness (Sailor and Fan, 2002; Changnon et al., 1996; Knowlton et al., 2004). It is revealed that 70 000 deaths were occurred due to a summer heat wave in Europe, 2003 (Robine et al., 2008).

Recently, UHI became a significant predicament and measures that have been taken to mitigate through urban planning where different urban design options can enhance urban air quality and outdoor thermal comfort by reducing surface temperatures (Emmanuel et al., 2007). Mitigation measures that can be used to reduce UHI are manipulating urban structure (dimensions of the buildings and spaces between them, street widths and spacing), increasing urban cover (fractions of built-up, paved, vegetated, bare soil and water) and regulating urban metabolism (heat, water, and pollutants due to human activity) (Stewart and Oke, 2009).

Increasing urban shading with greenery is a successful option (Galenieks, 2017; Park et al., 2017; Zölch et al., 2016) as trees can mitigate the air temperature by evapotranspiration. Trees can intercept incoming solar radiation and preventing it from penetrating into street canyons, thus providing shade and cooling benefits (Matzarakis et al., 1999). Cooling effect of the urban vegetation depends on the foliage density and cooling capacity of the plant (Tan et al., 2010). Besides trees are utilizing a considerable amount of solar energy for the process of photosynthesis and as a result significant fraction of radiation will be retained instead of releasing to the atmosphere which would cause extra heating (Chandramathy and Arch, 2014). Researchers have proven that photosynthetically active radiation was reduced by 94% just penetrating 5 m into the canopy of Puerto Rican wet forest (Johnson and Atwood, 1970) and global radiation was reduced by 53% just penetrating 6 m into the canopy of a Malaysian rain forest (Yoda, 1974). Vegetation has the ability to reduce air temperature up to 5 °C by the evapotranspiration and its shading process (Akbari et al., 2009). Furthermore, trees help to reduce CO_2 through carbon sequestration and Ozone precursor levels in air, so it can reduce the greenhouse gases (GHG) of surrounding micro-climate directly and indirectly. Most cities are designed with vegetative surfaces in terms of urban forestry such as trees on curb sides, trees in centre-median (Tran et al., 2017; Kenawy et al., 2010; Akram et al., 2008), living green roofs (Getter and Rowe, 2006), green walls, green façade and turf areas (turf the paving, turf the parking areas, turf the urban gardens/parks). Average maximum daytime temperature could be reduced from humid cities like Hong Kong by 8.4 °C, City of Athens by 10 °C and Riyadh by 3.4 °C and Moscow by 1.7 °C by using vertical greenery (Alexandri and Jones, 2008; Santamouris et al., 2001).

Sri Lanka is also experiencing excessive day time temperatures in cities with industrial, commercial and domestic activities with a huge population and continuous constructions. Colombo is the main commercial metropolitan in Sri Lanka with a recent continuous development and it reports extensive temperature increments and extreme thermal insecurities inside the city. Hence this preliminary study will evaluate the feasibility to mitigate the UHI through vegetation installation by computer simulation with the adaptive use of a numerical simulation model software named ENVI-met (and LEONARDO) developed by Michael Bruse, of the University of Bochum, Germany (Elnabawi et al., 2013; Ozkeresteci et al., 2003; Huttner et al., 2008; Kittas et al., 2015; Jeong et al., 2015; Nice, 2011). Moreover, this paper explores the contributions of designed urban green strategies for its thermal comfort effects in order to enhance the awareness and affinity to use green alternatives in urban settings in tropical Sri Lanka. This research was conducted (a) to envisage the validity and feasibility of ENVI-met software in urban micro-climatic modeling in tropical Sri Lanka and (b) to identify the best possible green infrastructural strategies to maintain enhanced microclimatic conditions in tropical urban context to mitigate existing UHI.

2. Materials and methods

Methodology of the research is comprised of a case study with a field assessment and a simulation study.

2.1. Study area

Colombo Metropolitan Region (CMR) is located on the Sri Lankan West coast in lowland region at 6°56′N, 79°50′E with 1 m elevation from mean sea level and 5.6 million inhabitants approximately in metropolitan area. CMR is extending about 100 km in the North–South and 30 km in the East–West directions with a typical warm–humid tropical climate which is classified as Af (Tropical rainforest climate) in accordance with Koppen–Geiger climate classification (Kottek et al., 2006). Most of the city is classified as LCZ3 (48.1%), LCZ2 (8.9%) and LCZ8 (23.7%). LCZ1 (0.3%) and LCZ4 (1%) form a very small fraction of Colombo's built fabric (Perera and Emmanuel, 2007). The CMR climate is affected by Asiatic monsoon and existing high temperatures and humidity values (Fig. 1) are creating an inconvenient thermal environment throughout the year (Johansson et al., 2004). Some research studies on UHI issues had reported that CMR had temperature intensities ranging from 0.09 °C to 4.4 °C over the selected 'rural' areas (Perera et al., 2012).

2.2. Calibration of ENVI-met

Initial software calibration was completed in the premises of Civil Engineering Department, University of Moratuwa, Sri Lanka (6.7969°N, 79.9018°E) to test the feasibility of ENVI-met numerical model for tropical Sri Lankan micro climatic conditions. Three thermal sensitive receptors were installed in different surfaces that are made with materials comprised of diverse albedo values such as asphalt, cement and grass. Temperature variations were monitored throughout two successive warmest days of August 2016 (29th and 30th) by using automatic Graphtec data logger (GL240) for 48 h in five minutes intervals under free running mode as establishing the receptor knobs in two different heights (0, 1.5 m) along each pole.

Same locality was modelled inside the simulation software after the configuration (Fig. 2) and the building case study was calibrated to validate the simulation software. Simulation was conducted through numerical micro-climate model ENVI − met by using hourly ambient climatic data from Colombo, meteorological weather department. Scatter distribution diagram was prepared to(a) monitor temperature measurements (b) validate the accuracy and (c)test the suitability of model with acquired R^2–Coefficient of determination values to standardize the ENVI–met model.

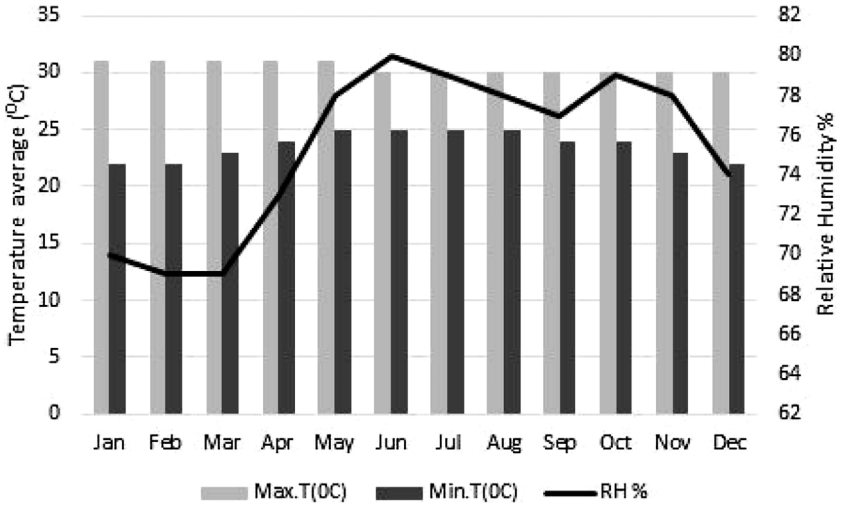

Fig. 1. Annual average maximum/minimum temperature and relative humidity in Colombo metropolitan, Sri Lanka.

2.3. Configuration of site in ENVI-met

The effect of different green vegetation infrastructural strategies on temperature were examined by modeling a selected urban micro-climatic context during the second phase of the study. 4.58 ha area from Bambalapitiya city (Fig. 3) in CMR (6°53′20″N and 79°51′24″) was selected as the urban setting as this area is highly dynamic with commercial, industrial and residential events. This area is North-South oriented, situated in coastal belt of wet zone and having hot and humid climatic characteristics with an average maximum temperature at 3 pm as 33.2 °C and higher relative humidity value of 90% at 5–6 am for August.

2.4. Selection of suitable green alternatives

Three green structures (trees on curbsides, green roofs and green walls) were selected for the experimental site by considering factors such as site characteristics, available spaces and usage of the area. Six case studies with different green infrastructure were designed under this study as mentioned in Table 1 and all six case studies were integrated into numerical microclimatic ENVI-met model SPACES (Fig. 4).The meteorological input data for the simulations are summarized in Table 2. Hourly climatic data were obtained from Colombo- Ratmalana meteorological station. T_1 represents the base case or the existing condition in Bambalapitiya city and that was considered as the UHI scenario.

All microclimatic locations were created into a grid of 60 × 60 × 30 cells with 5 nesting grids and the respective grid was rotated 20° from North to rectify the block structure. Selected trees and plant species which are dominant in tropical Sri Lanka were designed in the ENVI-met database by considering the suitability to the location, available space, crown diameter, trunk height, plant area coverage ratio, leaf area density (LAD) and leaf area index (LAI) to represent as the vegetation strategies

To design green roofs and green walls grass characteristics were used. In addition, for designated Trees 8 m height and 4 m crown diameter was selected. The arrangement of streets, buildings and albedo of the surface materials were kept constant in all case studies to segregate the effects of vegetation from other urban contexts. Finally, the information were extracted from IDT files of ENVI-met such as T_a – air temperature at 1.5 m height (average height of standing person and people feel the heat with that height), and relative humidity at 3 pm to compare with base case (Existing UHI (T1)) and to determine the outdoor temperature values.

Fig. 2. 3D model of calibration location by ENVI-met.

Fig. 3. Selected urban context for modeling-Bambalapitiya city in CMR.

Table 1
Selected cases with green alternatives.

Case 1	T_1	3- a	Existing condition (Considered as UHI)
Case 2	T_2	3-b	Trees in Curbsides
Case 3	T_3	3-c	Establish green roofs in maximum conversion scenario (100%)
Case 4	T_4	3-d	Establish green roofs in reliable conversion scenario (50%)
Case 5	T_5	3-e	Establish green walls in reliable conversion ratio
Case 6	T_6	3-f	Combined option with Trees in curbsides + 50% Green roofs + 50% Green walls

3. Results and discussion

3.1. Calibration results

ENVI-met model validation in tropical Sri Lankan conditions were examined by plotting measured real time in–situ temperature values against simulated temperature values for three different surfaces with different albedos. Simulated and observed actual temperature measurements showed similar pattern of variation trend and coefficient of determination (R^2) values were analyzed by using scatter plot distribution in elevations of 0 m (ground surface) and 1.5 m (Figs. 5a, b, 6a, b and 7a,b). Ground level (0 m) and 1.5 m above ground level R^2 values for asphalt, cement and grass were 0.9128 and 0.7834, 0.959 and 0.8058 and 0.8821 and 0.9155, respectively.

Several earlier studies conducted to validate ENVI-met micro climatic model to fit with urban contexts in several countries were analyzed by contrasting the real ground measurements and simulated values (Salata et al., 2016). Coefficient of determination for air temperature (T_A) in Freiburg (Lee et al., 2016), Oberhausen (Müller et al., 2014) and Berlin (Jänicke et al., 2015) in Germany were 0.85, 0.97 and 0.87, respectively.

R^2 values for ENVI-met model calibration were recorded as 0.81 in Beijing, China, 0.96 in Bilbao, Spain and 0.52 in Changwon City, South Korea for temperate climatic urban settings (Acero and Herranz-Pascual, 2015; Song and Park, 2015). ENVI- met model calibration gave R^2 of 0.69 (Wang et al., 2016) in humid continental climates (Toronto) and $R^2$of 0.89 tropical desert climatic conditions in Phonix USA (Hedquist and Brazel, 2014).

The only reported R^2values in tropical urban settings for Kuala Lampur and in Putrajaya ENVI- met model were 0.96 and 0.69 respectively (Ghaffarianhoseini et al., 2015; Qaid and Ossen, 2015). In this study, each and every value showed a realistic conformity since all R^2 values observed were almost equal to 1, therefore the simulation model can be accepted, and it can be envisage that ENVI-met microclimatic model is feasible to utilize in tropical Sri Lankan urban settings.

3.2. Site modeling results

Modeling results of existing condition (T_1) was considered as UHI effect which already exists in the city. Average temperature values were varied in the range of 27.88–34.67 °C while the highest temperature value of 34.67 °C at “1500”h and the highest relative humidity value of 83.77% at 0500 h have been reported.

This highest temperature (34.67 °C) may result due to emissivity and thermodynamic characteristics of construction materials and the lack of existing vegetation in the area. Materials which have higher albedo values such as asphalt in roads, cement and concrete bricks in buildings can absorb solar radiation and re-radiate as heat waves to the environment. The thickness and composition of materials for walls and roofing were considered in ENVI-met, simulations (Huttner and Bruse, 2009). Default thickness, heat absorption, heat transmission, reflection, emissivity, specific heat, thermal conductivity and built material density (Huttner and Bruse, 2009) which can control the observed higher temperatures of different materials in Colombo Urban context were considered during ENVI-met software simulations.

The temperature contour maps that have been prepared through the analyzing tool (LEONARDO) in ENVI-met application are shown by Fig. 8. Temperature fluctuations of the urban settings can be clearly identified through colour variation compared to existing condition (T1).

East- west oriented walls of the city buildings were made up of glass and they were capable of reflecting thermal waves in multiple times. East – West oriented windows were not constructed since that brings more direct solar radiation into the building which resulted in, elevated

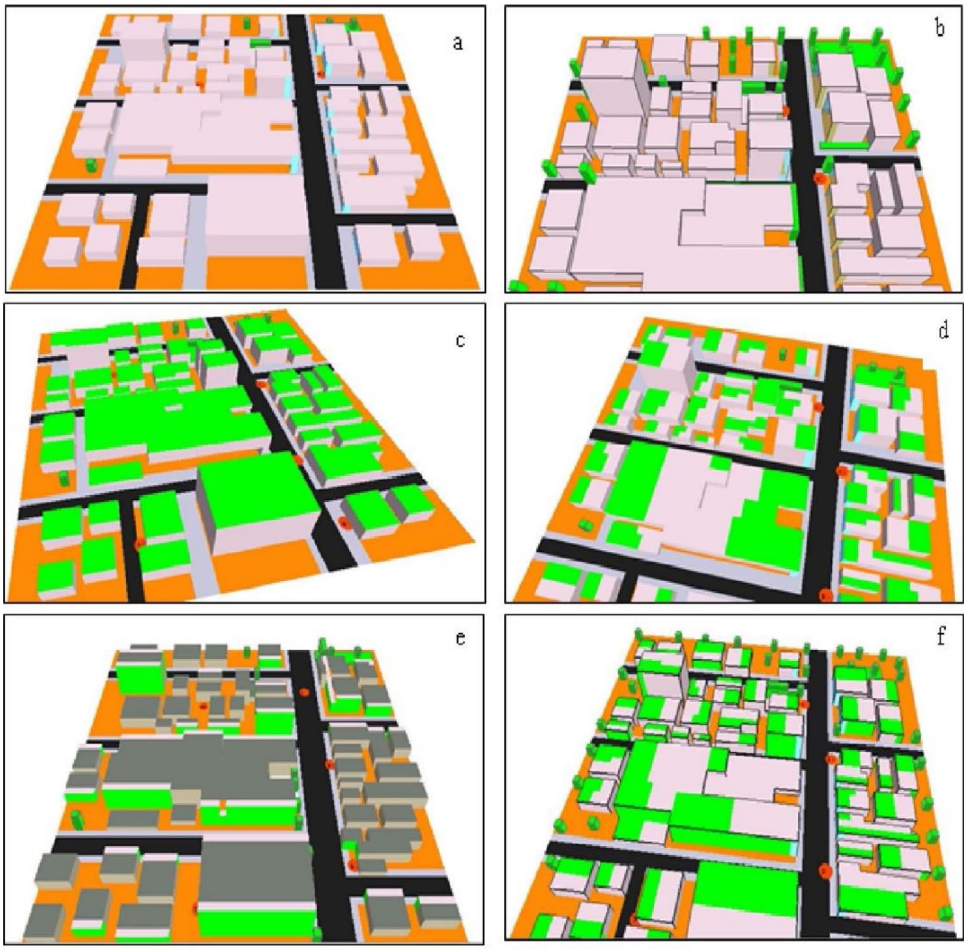

Fig. 4. Models for each cases with green alternatives. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
a- T1 (Existing UHI effect), b- T2 (Trees is curbsides), c- T3 (100% green roofs), d- T4 (50% green roofs), e- T5 (Green walls, reliable ration) Trees in curbsides + 50% green roofs + green walls reliable ratio), f- T6 (Combination of all options).

Table 2
Used climatic parameters.

Location	Bambalapitiya, CMR	
Climate type	Hot and humid	
Simulating duration	24 h	
Start time	0100 h	
Wind speed (m/s)	2.8	
Wind direction	270°	
Roughness length at the measuring site	0.1	
Specific humidity at model top	9	
RH in 2 m (%)	75	
Adjustment factor for solar radiation	1	
Initial temperature	28 °C	
Initial soil condition (K)	Upper	301.15
	Middle	300.95
	Deep	299.65
	Bed rock	299.15

indoor temperatures during constructions. Further, with glass, the short wave radiations can easily pass through and (glass block the long wave radiation and reflect them back) emit from the surfaces with low temperatures to leave the room. This is principally a mini greenhouse effect and it leads to warm the indoor atmosphere.

City heat deduction was reduced due to direct sea wind-jamming effect with existing building geometry. Consequently, day time of the city acquires inconvenient heat-load for city dwellers and night time shows comparatively lower heat-load compared to day time. However, high water vapour capacity or relative humidity in the atmosphere further deteriorates the thermal comfort of the city dwellers and occupants.

The Aspect Ratio-AR (the ratio between building height and road width) which is a direct factor of canopy geometry in a location is very important factor to rule the canyon temperature in urban settings.

Street canyons are classified as symmetrical or asymmetrical and the selected location was filled with asymmetrical street canyons with different height buildings. The relationship between AR relative to solar angle must be considered when interpret the micro-climate and thermal comfort conditions of an individual street canyon. AR dominates the duration and magnitude of the energy regime of a street canyon (Ali-Toudert and Mayer, 2007; Qaid and Ossen, 2014). It enhances the surface temperature and greater radiant energy will be dissipated to the canyon (Yoshida et al., 1990; Coronel and Alvarez, 2001) where it increases the area of exposing (AR = 1). When deeper the canyon (AR > 2), it lowers the surface temperature significantly due to shading effect encountered by buildings (Yoshida et al., 1990; Coronel and Alvarez, 2001).

Orientation of the canyon decides the amount of energy which occurred in street canyon by controlling the duration and magnitude. This site can be regarded as North-South oriented since the site was highly exposed to solar radiation throughout whole day (Ali-toudert and Mayer, 2006; Ali-toudert and Mayer, 2007; Ali-Toudert et al., 2005).

Day time temperature in modeling options with green infrastructures were showed a significant drop compared to T1 within the time range of “1100 h” to “1600 h” (Fig. 9). Peak of the temperature was recorded at “1500 h” (considered as UHI condition) and each option could give the best temperature reduction at that particular time, “1500 h”.

It has been recorded a maximum day time temperature reduction of 1.87 °C (percentage reduction compared to T1 is 5.39%) during peak hour, “1500 h” (1500 h was considered as the peak hour for all further

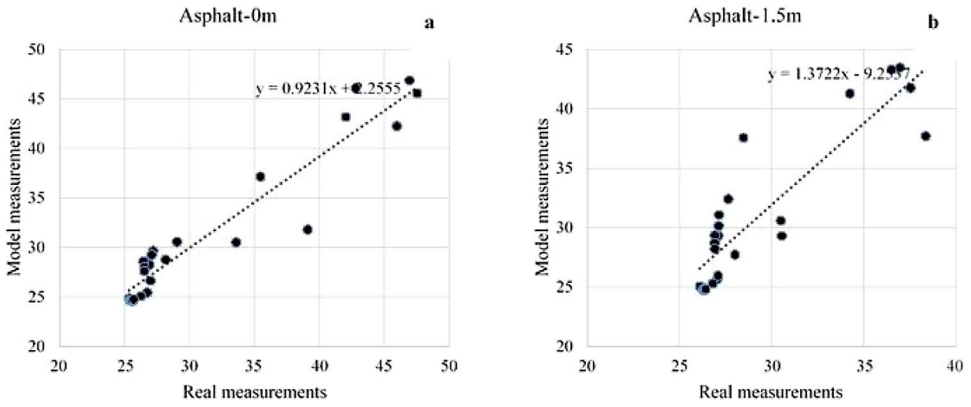

Fig. 5. (a) Model values vs. Real ground values for zero height (b) Model values vs Real ground values for 1.5 m for Asphalt.

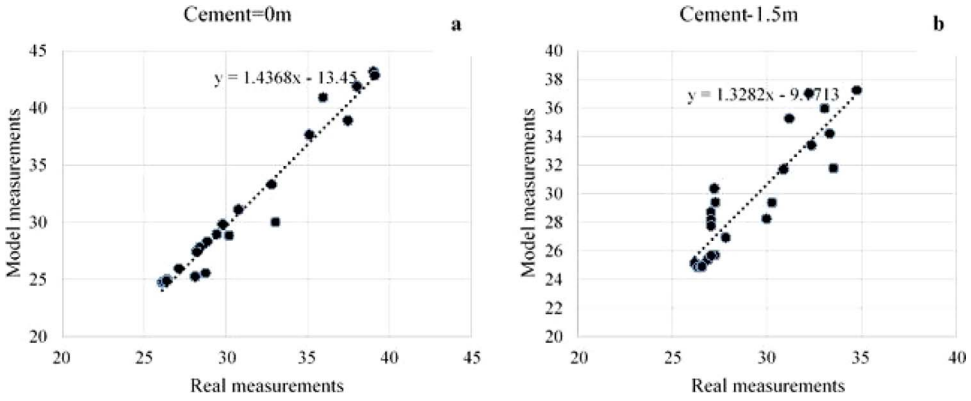

Fig. 6. (a) Model values vs. Real ground values for zero height (b) Model values vs Real ground values for 1.5 m for Cement.

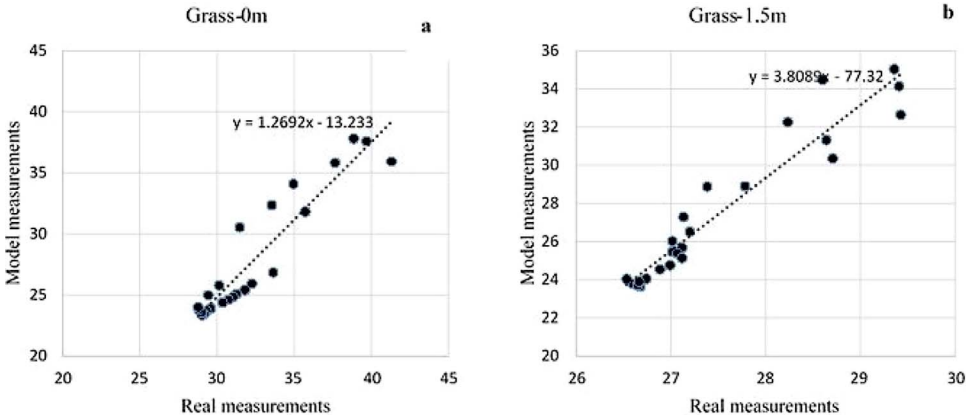

Fig. 7. (a) Model values vs. Real ground values for zero height (b) Model values vs Real ground values for 1.5 m for Grass.

comparisons) in trees in curb sides (T_2). Vegetation can mitigate heat of its microclimate directly and indirectly. Carbon sequestration of trees is one of such reason that can cause for this heat reduction indirectly by removing CO_2 that can retain heat (Kiran and Kinnary, 2016). According to Kiran and Kinnary (2016), 73.59 tons of CO_2 is removed by trees planted in curb sides of Vadodara city in India which represents 22% of the City's estimated total CO_2 production (Kiran and Kinnary, 2016). Further, the transpiration process of trees can increase the humidity of the surrounded area. Increment of actual content of water vapour in air can increase the relative humidity and then inversely reduce the air temperature of the location.

Relative humidity (RH) values in planted trees in curbsides (T2) were increased during whole day and maximum RH value of 69.5% at "1200 h" was recorded. The biophysical processes of transpiration and evapotranspiration of vegetation may be the reason for humidity increment.

Several cross sections of street canyons from the urban context were explained with building heights as depicted in Fig. 10 and Fig. 11. Location A in Fig. 11-a, street canyon is composed with 32 m building from wind direction. Wind can enter by pitching to lower elevations, blow through road area and it can easily exit with retained heat, particles and gases as the opposite building height is low. Heat can be removed by vegetation through absorbing as energy for photosynthesis process and some shading for surrounded area can be provided by taller building structures.

In location B- Fig. 11-b, building heights are considerably high, however distance between two buildings permits heat removal. In wider canyons, temperatures inside the canyon are dominated by the proportionally larger street surface and the fact that it is more exposed to direct solar radiation (Alexandri and Jones, 2008).

In both locations of A and B, temperature rise is depending on material of road surface (Huttner and Bruse, 2009) and the canopy is wide open for solar radiation in any position of sun in whole day as road was North-South oriented. As the height of the tree is only 8m, it

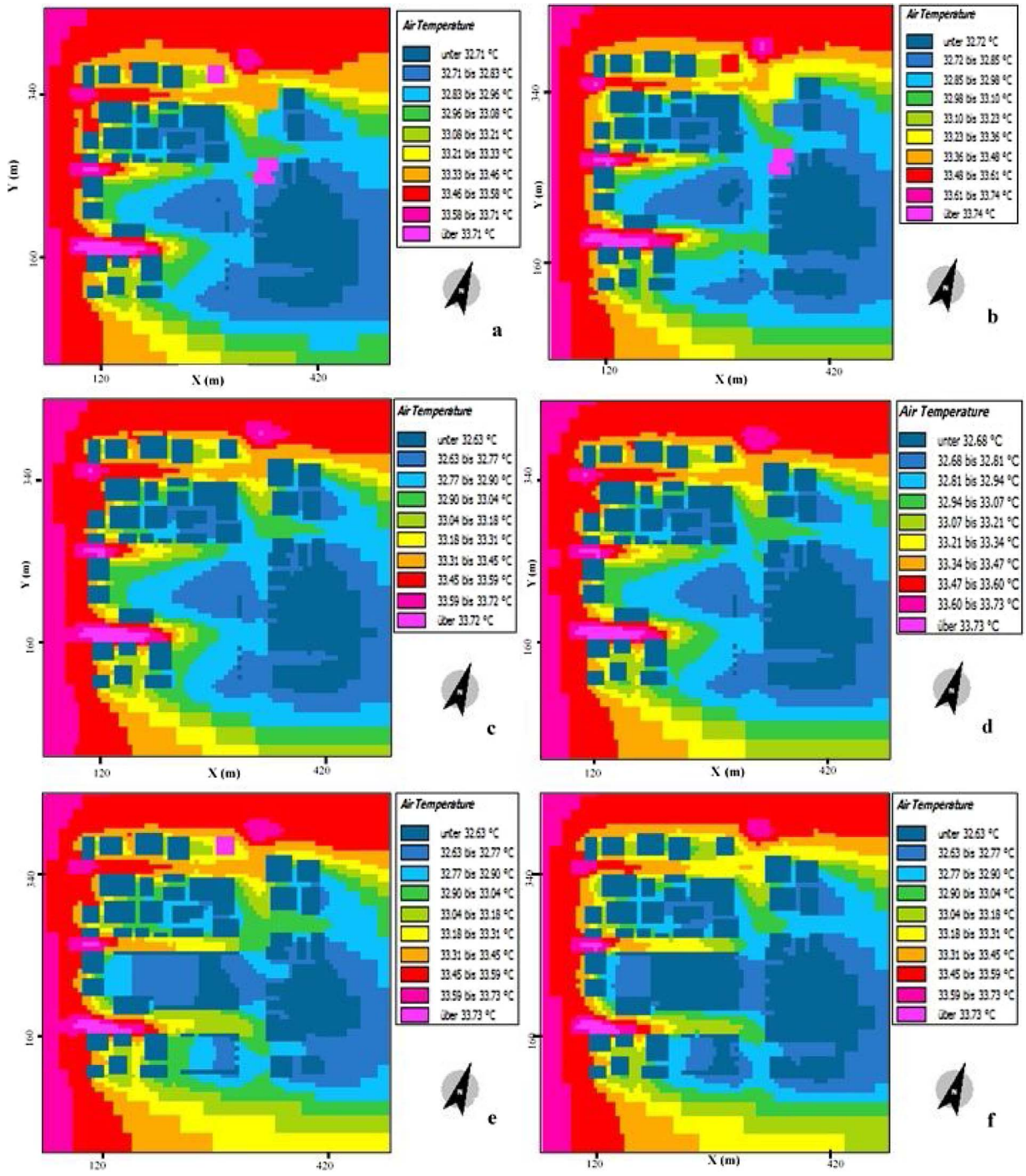

Fig. 8. Temperature profile in Bambalapitiya by LEONARDO: a-T1 (Existing), b- T2 (Trees in curbsides), c- T3 (100% green roofs), d- T4 (50% green roofs), e- T4 (50% green walls), e- T6 (Combination of all options). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was not exceeding the building heights in almost every space in the site, so shade effect cannot perform a significant effect for heat reduction. Processes of photosynthesis and transpiration may supportive for temperature drop (Kiran and Kinnary, 2016). If trials with wider canopy size and tree height may bring different results, however it should be noted that denser and wider crowns may retain pollutants and heat absorbing gases by avoiding removal with wind currents.

Significant amount of incoming solar radiation can be absorbed by crown with the building heights of location C in Fig. 11-c, (Pretzsch et al., 2015). However, the main limitations are the available space and street canyon is narrower as considered in feasible tree types. Shade effect can be contributed for cooling in this case and wind direction was laying along the street. Consequently, remaining heat, particles and gases can be removed with wind currents. When compared to UHI certain areas were observed higher temperatures after the introduction of new options. This may be happened owing to heat waves were trapping inside the canopies (Pretzsch et al., 2015; Chen et al., 2009) and water drop load of evapotranspiration. However, this should be studied further for accurate clarifications.

Converting whole roof area of selected location to green roofs (T3) gave the maximum peak hour temperature value at “1500 h” as 32.88 °C while the highest relative humidity (83.51%) was recorded at “0500 h”. After adding the green option, UHI peak temperature has been reduced by 1.79 °C. Green roof can act as a constant heat sink

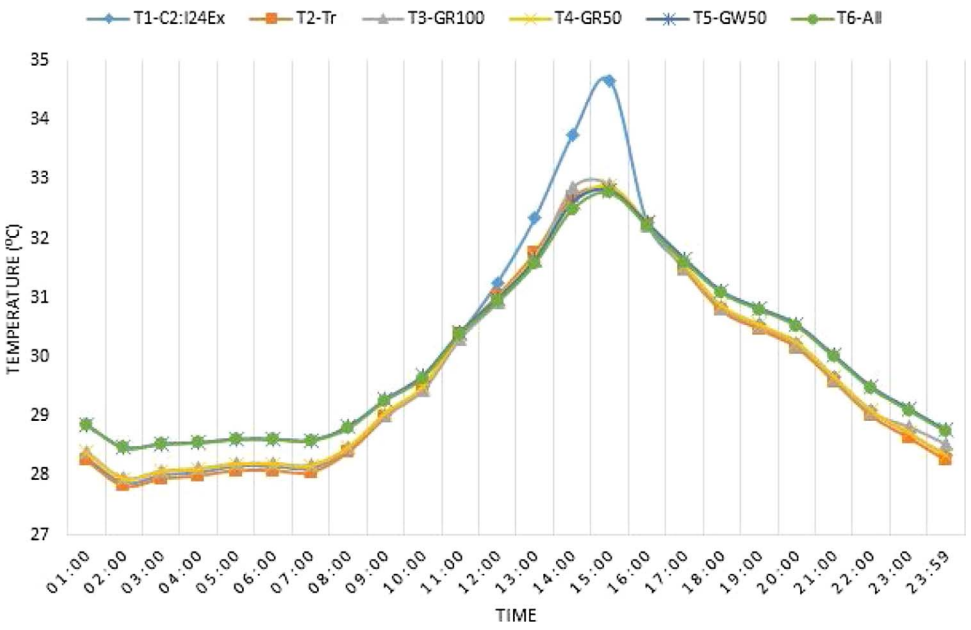

Fig. 9. Temperature variation of each green infrastructure options with time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

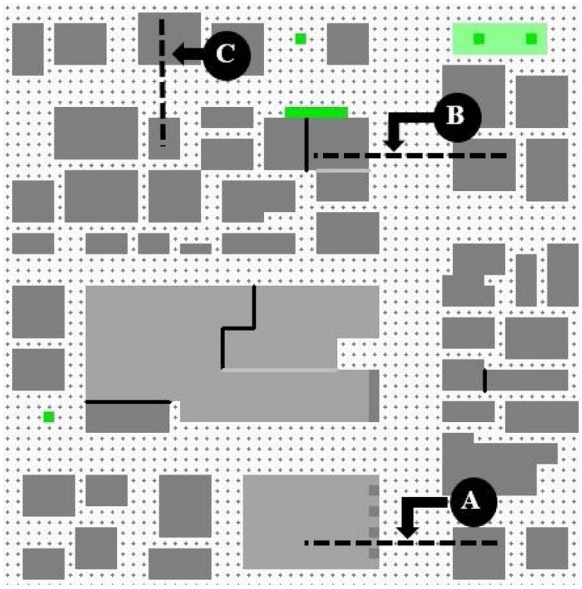

Fig. 10. Cross sectional locations considered for AR.

when evaporative heat transfer and absorb lesser radiative energy than a concrete surface does as a key property of a green roof is its low solar absorbance (Saiz, 2006). Therefore, it causes lower surface and air temperature, thus reducing the heat flux through the roof when compared with concrete surface. With energy distribution, air masses enter the canyon much cooler from the vegetative surface on the roof but heating back from concrete walls. Annual energy use savings were just over 1%, but summer cooling load has decreased by over 6% and reductions in peak hour cooling load in the upper floors reached 25% in Toronto, Canada due to this outdoor and indoor temperature reductions (Saiz, 2006). It has been reduced the electricity consumption in city of Adelaide, Australia by 2.56 Wm^2/Day after adding 30% of green roofs to the city (Razzaghmanesh et al., 2016). Other than temperature mitigations, green roofs can provide environmental benefits to the site. By replacing the common flat roof with a green roof in Toronto, environmental impacts were reduced by between 1.0 and 5.3% (Saiz, 2006).

Adding green roofs for 50% roof area was practiced in T_4 scenario. Recorded highest temperature value was 32.91 °C as UHI peak at "1500 h". Higher relative humidity values were observed at night while day time claimed lesser humidity. Temperature reduction was quantified as 1.76 °C when compared to the UHI temperature in peak. However, this was measured in 1.5 m height and roof is the element that can directly affect to the internal thermal comfort, they block all thermal waves, and solar radiations while providing a shade and reduce the temperature. Therefore, the simulated temperature values from the software were mainly contributed with the other materials surrounded by the receptor in this height. Hence, if it has been considered the roof surface temperature, it might give more effective results of lesser temperatures as it can create more comfortable thermal condition inside the canyon, when the building envelope is covered with vegetation. As this area had an intense building cover, roofs were obtaining most of the total area. In both options of 50% and 100% green roofing options have showed a considerable reduction of temperature due to that and it seems temperature can be reduced significantly, when vegetation covers the most of the area.

When comparing two options of 50% and 100% green roofing with each other, reduction from 100% green roof cover (1.79 °C) did not show a significant reduction with the temperature related to 50% green roof cover (1.76 °C). Roofs are to regulate the indoor temperature and total effect from vegetation to the temperature was the reason to reduce the outdoor temperature in this scenario. Measurements of indoor temperature conditions may show different results in both options.

Therefore, it can be ensured that the percentage of vegetative surface does not contribute to the outdoor temperature reduction at lower levels (1.5 m) in significant manner; however it can reduce the roof level temperatures. According to Alexandri and Jones (2008), wider canyons, smaller the effect of green roofs and green walls on its temperature decreases. Temperature values inside the wider canyons, are dominated by proportionally larger street surface and the fact that it is more exposed to direct solar radiation (Alexandri and Jones, 2008). Therefore, this might be another reason for the temperature reduction as this canyon is considerably wider with A2 highway and there were no much taller buildings exceeding 40 m for shading effect on that canyon.

In T_4, reliable amount of green wall addition to the building was determined by considering some facts. Whole set up was North-South oriented and East-West faced wall surfaces composed with glass walls, as most of buildings are commercial. Thus 50% of building walls were converted into green façades as shown in Fig. 3-e. Peak temperature was recorded as 32.81 °C at "1500 h", while giving higher humidity

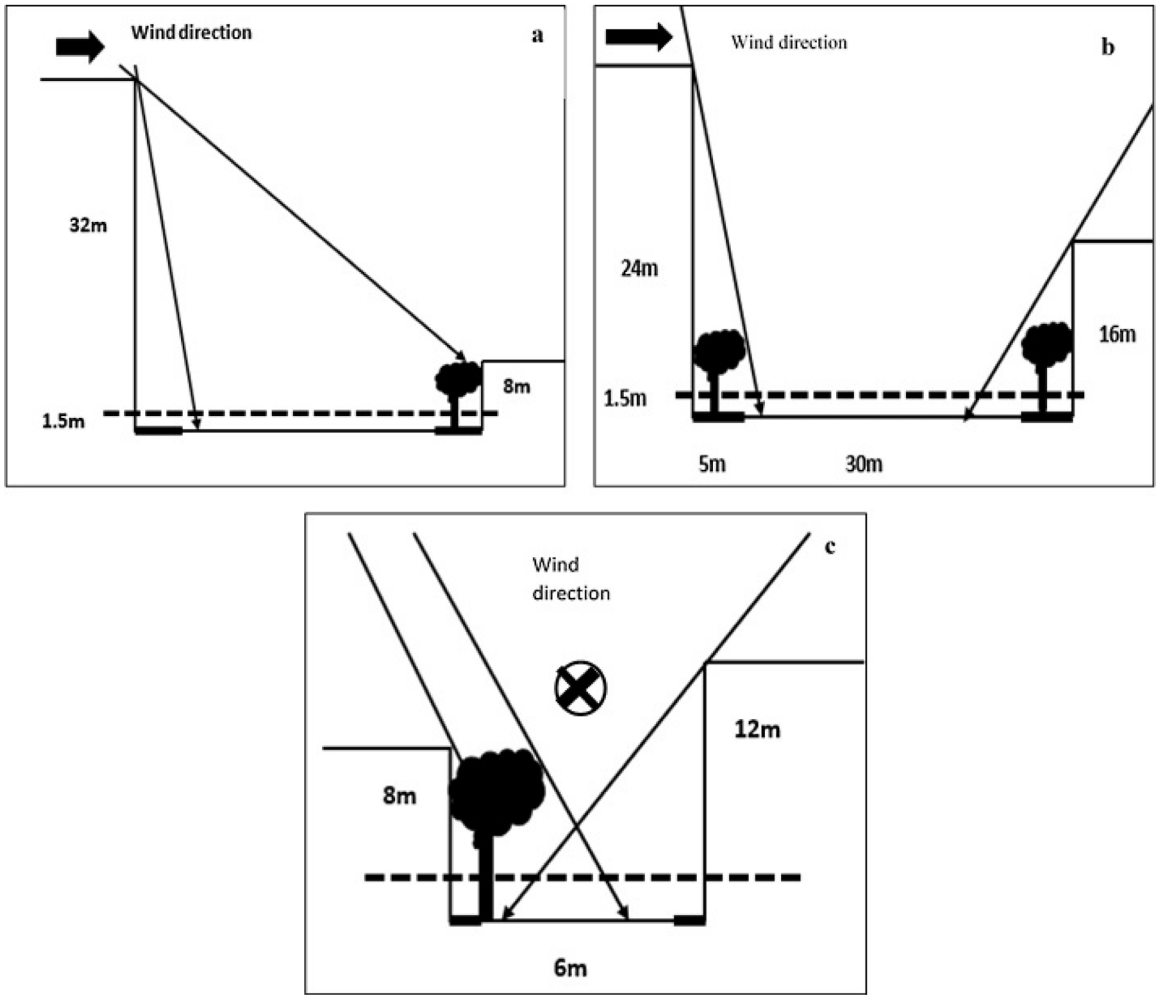

Fig. 11. Cross section of urban contexts (a- Location A, b- Location B, c- Location C).

values during night and morning where 78.9% was the highest RH that given at "0500h" in the morning. After manipulation with 50% green walls, it showed a daytime temperature reduction as 1.86 °C (5.36%) at "1500 h". The maximum temperature reduction of 8.4 °C in humid climates of Hong Kong with vertical greenery systems was reported in that relevant urban canyon (Alexandri and Jones, 2008).

Concrete and solid bricks were used for the construction of walls in the case of UHI and in 50% green walls (T5), vegetation covering was established on some surfaces where the emissivity and albedo values were changing. Emissivity is considered to measure the ability of material to emit infrared energy. Most organic and oxidized surfaces obtain emissivity values close to 0.95 and both concrete and plant surfaces claim emissivity value of 0.94 (Salvaggio and Miller, 2004). With comparatively higher albedo value of 0.3, grass or plants enhance the reflectivity of solar radiation instead of absorbing compared with concrete surfaces with 0.23 albedo. That may be a significant reason for the temperature reduction in vegetative walls than bare walls in UHI condition.

Using green walls in urban infrastructure as heat mitigation strategy is very successful as it can contribute effective temperature drop in a vertical plain. Unlike green roofing, green walls are attaching through whole vertical profile and vegetation can control the heated air mass throughout the canyon. A study done in Hong Kong, canyon air temperature decreased with green wall option by 3.9 °C, related to that urban context (Alexandri and Jones, 2008). Usually green walls have a stronger effect than green roofs inside the canyon for all climates examined (Alexandri and Jones, 2008). Nonetheless, green roofs have a greater effect at roof level and, consequently, at the urban scale. In this study, vertical vegetation was used in North-South oriented walls as considering the geometry of location. If added greenery to the walls that faced to solar direction, it may upgrade the results with higher reductions and it is recommended for future studies.

When considering T_6, all green options were practiced simultaneously. When established trees in curbsides + 50% green roofs + 50% green walls as combination, it has recorded the peak temperature value as 32.77 °C at 1500 h, while giving 78.95% as maximum relative humidity throughout the day at "0500 h". With green option manipulation, temperature had shown a significant reduction of 1.9 °C.

After merging all options together, consistent with the results, it could magnify the temperature reduction. When using all options together, it increased the vegetative surface in selected area (Shashua-bar and Hoffman, 2000). Therefore, this wider vegetative surface can decrease air temperature by direct shading of surfaces provided by trees in curbsides, by restraining solar heat gain through evapotranspiration of the whole vegetative area, and converting incident solar radiation to latent heat. This can increase the reflectivity by reducing the amount that can lies on low albedo materials of concrete or asphalt. Green walls and green roofs can reduce the solar heat gains on windows, walls, and roofs through shading and covering and can reflect most part of the radiation by higher albedo value. In addition, they can reduce the building long-wave exchange with the sky, because it can lower the building surface temperatures through covering and shading by façades. All vegetative surfaces are reducing the conductive and convective heat gain through evapotranspiration process and increase of

latent cooling by adding moisture to the air through evapotranspiration (Dimoudi and Nikolopoulou, 2003). Moreover, total vegetative fraction throughout the modeling site can sequestrate carbon load emitting through anthropogenic activities by photosynthesis (Kiran and Kinnary, 2016).

Maximum temperature reduction recorded in the study was 1.9 °C by using all options combination in an area of 4.58 ha. This would achieve a higher energy saving and ensure optimum thermal conditions to the city dwellers and occupants in CMR. Reduction of single Celsius or in decimals would be significant in UHI mitigation as it has been proven through an energy prediction model simulated in Houston, Texas, USA where 1.1 °C/2°F temperature reduction is projected to save annual energy cost by $82 million with a reduction of peak power of 730 MW (Konopacki and Akbari, 2002).

It was a potential reduction of outdoor temperatures by as much as 5 °C at critical times of early evening and early morning when it consider the effect of vegetation in linear parks in metropolitan cities in Arizona, such as Phoenix and Scottsdale (Ozkeresteci et al., 2003). A study which conducted in Greece to measure and simulates the microclimatic effects of a horizontal hydroponic pergola has proved a temperature reduction when compared to initial situation at 1.25 m height.

Temperature reduction was recorded as 0.48 °C from 50% planted area of atrium covered by pergola with leaf area density (LAD) of 2, while 0.58 °C reduction was given from 50% planted area of atrium covered by pergola with LAD 5 and 0.78 °C of reduction from 100% planted area of atrium covered by pergola with LAD 2 (Kittas et al., 2015). It should be pointed as all these values are relevant to their unique urban contexts, sizes, climatic parameters, so values of two different context from various countries cannot be compared.

Therefore, the study in CMR revealed that the maximum temperature reduction was reported in combination of all options and it was 1.9 °C and 5.48% reduction compared to existing UHI temperature. This reduction effect can be intensified through proper urban planning and landscaping of the area. As lesser relative humidity values create more thermally comfortable surroundings, adding green walls in reliable limits and combination of all alternatives can be nominated as suitable options to Bambalapitiya. However, for the most effective mitigation of UHI, this study proposes to use the combination of all alternatives together for CMR.

4. Conclusion and recommendations

Software calibration has proven that the ENVI-met is feasible to use in Sri Lankan climatic simulations in urban contexts with hot- humid climatic conditions with the results of R^2 of simulated temperature values against measured real ground values in same location, obtained from three different surfaces from two different heights.Presence of greenery can help to diminish the amount of solar insolation (and consequentially lower magnitude of heat storage) to the street canyon. Vegetation can cool surfaces effectively, hence this options are important for already constructed contexts as it could not change the albedo values and urban geometry.

Each green alternatives of trees in curbsides, green roofs 100%, green roofs 50%, green walls 50% and combination of all options, reported a reduction of 1.87 °C, 1.79 °C, 1.76 °C, 1.86 °C and 1.9 °C, respectively in time which peak temperature occurred. Combination of all options is the best suitable option in temperature reduction effect for tropical Colombo city with 1.9 °C (5.48%) total reduction as it can perform as a strategy to improve the human thermal comfort by reducing air temperature and reflected radiation. Hence this study can be concluded as greenery or vegetation can influence the existing microclimatic condition in a city and they can be used as UHI mitigation strategy in Colombo, Sri Lanka. Furthermore researches are required to assess the economical interpretation in terms of cost to select the best suitable alternatives among different options as future studies.

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